CIRP Journal of Manufacturing Science and Technology, Vol. 17, May 2017, pp. 18-31
DOI:10.1016/j.cirpj.2016.05.011

A novel approach for No Fault Found decision making

Samir Khan[a], Michael Farnsworth[b] and John Erkoyuncu[b]

[a] School of Mechanical, Automotive and Aerospace Engineering, Coventry University, England CV1 5FB, UK
[b] Manufacturing and Materials Department, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

Abstract

Within aerospace and defence sectors, organisations are adding value to their core corporate offerings through services. These services tend to emphasize the potential to maintain future revenue streams and improved profitability and hence require the establishment of cost effective strategies that can manage uncertainties within value led services e.g. maintenance activities. In large organizations, decision making is often supported by information processing and decision aiding systems; it is not always apparent whose decision affects the outcome the most. Often, accountability moves away from the designated organization personnel in unforeseen ways, and depending on the decisions of individual decision makers, the structure of the organization, or unregulated operating procedures may change. This can have far more effect on the overall system reliability – leading to inadequate troubleshooting, repeated down-time, reduced availability and increased burden on Through-life Engineering Services.

This paper focuses on outlining current industrial attitudes regarding the No Fault Found (NFF) phenomena and identifies the drivers that influence the NFF decision making process. It articulates the contents of tacit knowledge and addresses a knowledge gap by developing NFF management policies. The paper further classifies the NFF phenomenon into five key processes that must be controlled by using the developed policies. In addition to the theoretical developments, a Petri net model is also outlined and discussed based on the captured information regarding NFF decision making in organisations. Since NFF decision making is influenced by several factors, Petri nets is sought as a powerful tool to realise a meta-model capability to understand the complexity of situations. Its potential managerial implications can help describe decision problems under conditions of uncertainty. Finally, the conclusions indicate that engineering processes, which allow decision making at various maintenance echelons, can often obfuscate problems that then require a systems approach to illustrate the impact of the issue.

Keywords: maintenance, decision making, No Fault Found, accountability

1 Introduction

The business model for the provision of a wide variety of high-value capital assets, such as aero engines, trains and medical scanners, is undergoing a fundamental shift (Baines et al 2007, Baines et al 2009). There is now a growing value in maintaining the life of a manufactured product throughout its lifecycle, and a number of services have grown to meet this need. A field that stems out from the need to guarantee performance and function of high value assets over their operational life cycle has been called Through-life Engineering Services (TES). According to Roy et al (2013), TES accounts for over 55 % of revenue for high-value manufacturing companies within the aerospace and defence sectors. For example, maintenance is a service often borne by the end user; this is now evolving into a service-based model in which a maintenance provider takes over the responsibility for the operability and maintenance of the asset (Zhang Z, and Chu X 2010).

This is seen within a number of aerospace companies where the time-limited contract for operating a particular service is given to a company who then lease the asset (engine) from its owner and contract with a maintenance company under a service level agreement to ensure availability of the asset; often the provider of the asset. Such a business model provides motivation for improving the maintenance process in order to reduce through-life costs and maximize profits on those contracts. System maintenance, in the context to through-life engineering, has become essential to gain a competitive edge within the service delivery market (Roy R et al, 2013). Since all systems (or assets) are unique, there will inevitably be uncertainty that will influence their operation and the efforts required to maintain system availability.
However, to manage uncertainty, organisations need to increase interactions amongst themselves; to carry out distributed decisions with existing information and decision technologies. Examples of the results of such interaction are:

- The large amounts of data collected and processed
- The proliferation of displays for presenting information in a form suitable for supporting decision making at different echelons of an organizational (or functional) hierarchy
- The massive exchange of data and information among the nodes of a distributed organization.

However, these developments of effective systems and informatics are not only dependant on the available technology (such as the sensors, databases, communications systems and human-computer interfaces) but also on the structure of the decision making organizations and the cognitive processes embedded in the organisation ethos.

Depending on the granularity in system requirements, humans play a vital role in organisational processes. In this context, the human continues to occupy a central role in decision making. The structure of the organization might affect the human decision maker's ability to work effectively under time pressure in a stressful environment (such as the one experienced by air traffic controllers, foreign exchange traders, military commanders in battle, or the operators of the control centre of a power plant during an emergency). However, an organization at times may exhibit dynamic phenomena that were not anticipated during the construction of the organizational structure.

There is much anecdotal evidence from engineering managers that their organizations can act in an unpredictable manner; away from decision makers who were assigned specific responsibilities to manage lower echelons. Changes in organization structure, such as access to decision support systems, can change the sensitivity of the performance measures to the actions of different decision makers. Furthermore, the choice of strategies on the part of these decision makers affects which one has most impact on performance. This shift in responsibility can be viewed from both positive and negative perspectives. In the former, it is desirable for control to mitigate the chances of a failure. Kahne (1983) has highlighted this connotation while discussing a command, control, and communication system. According to the author, in order to maintain system performance, responsibilities must be able to move (within the organisation hierarchy) through a large scale system. This is to adapt to any structural changes in the system. However, from a negative perspective, shifting responsibilities can lead to unforeseen (or undesirable) situations. For example, moving away from accountability executives (who should hold the positions of responsibility in favour of subordinates), can cause the performance of an organization to deteriorate if, what were seen to be efficient (and effective) means of processing information, are modified. Even if the structure is designed so that the overall task is performed without overloading employees, it can result in a wide range of performance depending on the strategies chosen by the decision makers. Therefore, it is important to ensure that strategies that are mutually acceptable are most regulated and standardised within the industry.

One problem that causes a lot of confusion during aircraft maintenance is the No Fault Found (NFF) phenomenon. NFF has been described as “a reported fault for which the root cause cannot be found” (Khan et al, 2015). This can be an output from a failed diagnostic process, which may comprise of a sequence of interlinking events – perhaps at different maintenance levels. NFF is a disruptive mechanism for TES. From a financial point of view, this causes a burden to almost everybody associated with the through life support service i.e. from the operators and customers, to the manufacturers and their suppliers. The direct investment of resources and time to investigate NFF events on the business is not easily quantifiable (Erkoyuncu et al, 2016). These can be costs such as those incurred within the supply chain, maintenance performance, as well as indirect effects such as customer perception and nugatory maintenance efforts. One notable gap identified in current NFF literature is regarding the characteristics that limit the NFF decision making process (Khan et al, 2014a). Based on this, this research paper aims to provide more insights to how NFF related decisions actually move within organisations and therefore addressing the question: "what are the characteristics that can enhance or limit the NFF decision making process?"

The paper makes use of information provided by three major participating aerospace organisations; that have chosen to remain anonymous in the publication – they included a systems integrator, a components manufacturer and a systems operator. The research work explored their management strategies on dealing with NFF events during maintenance activities. The aim was to understand how their decision making processes impact their business environment and to verify what characteristics enhance (or constrain) the organisations from making those decisions. Such analysis can allow the identification of accountability and dominant decision makers within their management hierarchy. Some recommendations are made for improvements by directing work towards increasing the efficiency of information flow in large scale organizations. However, this work can ultimately help in introducing policies within organisations in order to avoid any undesirable non-accountability situations. A method for modelling the decision making processes and understanding their impact across organizations is also outlined.
The novelties in the paper can be summarised as:

- Evidence of industrial attitudes regarding the NFF phenomena
- Identification of the drivers that influence the NFF decision making process
- Addressing a knowledge gap by developing management policies
- An NFF process map across three organisations – as a Petri net model

The rest of the paper is structured as follows: Section 2 discusses the related literature associated with the problem. The authors note the interactions that take place within organisations and how NFF manifests itself within them. The following critique reveals the industrial attitude towards the problem and what influences the NFF decision making process. Section 4 presents the research methodology on how this research was carried out. This is followed by the interview responses in Section 5, which were taken during the course of this research. This section also highlights the importance of establishing policies for managing NFF problems and introduces five key processes that must be controlled by these policies to mitigate NFF. Section 6 builds upon the knowledge acquired from the literature and interviews to map the NFF decision making process (as a Petri net model) across three organisations. Finally, the conclusions and future work is enumerated.

2 Background Literature

2.1 Why is NFF an issue?

The existence of the NFF issue has significant negative impact upon critical system stakeholder requirements, which at the top level, includes systems safety, dependability and life-cycle costs (Khan et al, 2014a). To deliver stakeholder requirements efficiently, it is essential to prevent, or at least, reduce the level of impact that NFF can have on a business operation. From a technical standpoint, a 'No Fault Found' tagged component is the result of an unsuccessful (or inefficient) troubleshooting regime of an unscheduled maintenance activity.

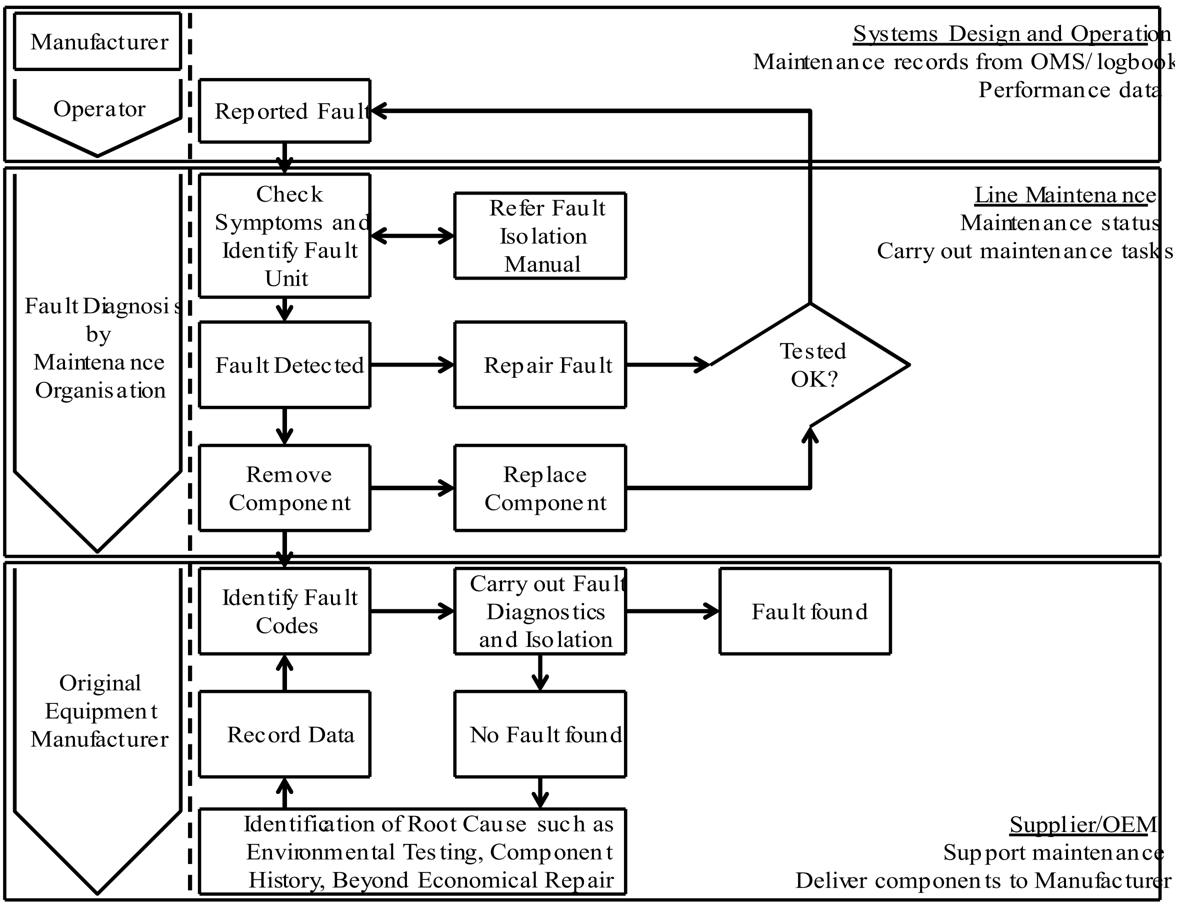

Figure 1: The Stakeholders and their Interaction at Component level (Khan et al 2015)

In order to understand the problem, consider Figure 1 which illustrates the complexities with stakeholders and processes involved during the maintenance process of a component's life cycle. These include the manufacturer[1], the operator and the supplier. The interactions that take place between the stakeholders are explained in Table 1:

Table 1: Organisational interactions

Between System Design and Operation	The Manufacturer is the design authority and provides maintenance support. Maintenance Documentation, Service Bulletins (SB) and Service Instruction Letters (SIL) all come from the Manufacturer. The Manufacturer often receives Maintenance Support Requests from the Operator and can also be asked for Maintenance Data from the Operator. The Aircraft is the subject of consideration, which is, amongst others, usually equipped with some form of On-Board Maintenance System (OMS), Logbook and technical documentation, etc. The Operator will receive the Maintenance Records from the aircraft's OMS/Logbook. In response, the Maintenance Organisation (or the operator's Engineering Department) will carry out Maintenance and deliver this information in some suitable format to the OMS and the Logbook (on board the aircraft). This department will receive Performance Data from the aircraft and will then provide the required Engineering Support.
To / From Maintenance	Line Maintenance will receive Maintenance Status information from the Aircraft via the Logbook and will perform the required Maintenance Actions. They will make corresponding Logbook Entries, to document the Return-to-Service (RTS) status. Shop Maintenance will receive Unserviceable components from Line Maintenance for testing, troubleshooting, calibration, repair, etc. It will provide Serviceable components for replacement. Shop Maintenance will deliver Unserviceable SRUs to the Supplier or Original Equipment Manufacturer (OEM) of that equipment for testing, troubleshooting, calibration, repair, etc. It can receive Serviceable SRUs from the Supplier/OEM in return.
To / From Supplier/OEM	The Supplier/OEM will support the Shop Maintenance by replacing Unserviceable units with Serviceable ones. Unserviceable units may undergo bench testing, troubleshooting, calibration, repair, etc. They can even reach their End-of-Life and Beyond-Economical-Repair status. The Supplier/OEM will deliver Systems/Components to the aircraft Manufacturer for initial production, and can also sometimes receive unserviceable/rogue Systems/Components back

Within the interactions highlighted in Table 1, a number of issues can arise:

[1] This can also be the system integrator

- The Original Equipment Manufacturer (OEM) may not understand the circumstances of a failure (Khan et al, 2014b). NFF is inherently a by-product of a lack of detail given by the environment in which the failure occurred, and the testing inability to replicate that environment and fault. In other words, a NFF is sentenced by the supplier, or repair station, due to a lack of incoming information about the part and/or the bench test procedures are too restrictive. It means that a test bench where actual environmental condition is reproduced may be necessary in finding the cause of NFF.
- Reliance on the Acceptance Test Procedure to identify faults (Knotts, 1999). During the troubleshooting procedure, the manufacturer will have issued a set of procedures (for particular fault codes/failure modes) that were developed during the system design phase. However, when these fail to identify the problem, other resources must be brought to bear during system operation – help escalation channels, technician training, supporting documentation, etc. Due to this, it is often difficult to define a fixed set of test procedures that can verify the full functionality of a component. As a consequence, it will lead to a log report that contains spurious fault detection, e.g. operator/pilot reports on faults may not correspond to the test logs, resulting in overlooked maintenance issues.
- An over-sensitive BIT[2] system intolerant of intermittency (Khan et al, 2014b). The design of a BIT system is a non-trivial task and relies deeply on the knowledge of all the system interactions. As electronic equipment evolves into ever more complex systems, BIT is increasingly depended upon to provide in-situ fault detection and isolation capabilities. Failures reported by over-sensitive BIT tests can be costly, and are likely to result in component replacement, recertification, or inevitable loss of availability of the equipment. The nature of BITs will be, in some way, dependent upon a set of pre-defined statistical limits for the various parameters which are being monitored. It is important to recognize that BITs will report failures when either they have exceeded a specified threshold, or when the intermittency of the BIT measurements throws the test results outside of the testing limits. The former of these is a direct result of component failure, for example a burnt out resistor. The latter occurs when a measured parameter, which has intermittent errors, are measured by an instrument having its own noise.

- Intermittent faults not detected by test equipment (Qi et al, 2008). Intermittency is arguably the most problematic of the NFF events due to their elusive nature, making detection by

[2] Built in tests (BIT) is a mechanism that permits a system to test itself. Engineers design them to meet specific requirements, such as high reliability, lower repair cycle times, etc

standard test equipment difficult. The faulty state will often lay dormant until a component is back in operational use, where it eventually causes further unit removals unless a genuine cause is found. It should be emphasized that these failures are not always present during testing, which make them troublesome to isolate. This situation can result in repeated removals of the same equipment for the same symptom, with each rejection resulting in the equipment being tagged as NFF. At this stage, there is a high probability that there will be loss of system functionality, integrity and perhaps, even an unacceptable compromise in safety requirements.

- The nature of repairs does not reflect the original failure (Khan et al 2015). This highlights that a fault was isolated, but it does not related to the root cause or fault symptom. The original defect is likely to re-appear, and as a result of unsuccessful troubleshooting attempts it will directly result in unscheduled maintenance jobs.

- Multiple rejections for apparently the same failure (Khan et al 2014a). The ability to recognize a failure is of paramount importance in mitigating the effects of NFF events. The key to distinguishing failures is to implement the necessary procedures to track the underlying conditions in which they occur; like the environment, the platform on which the components was installed, number of operating hours/cycles, number of hours since its last overhaul and a genuine reason for the generated removal codes. In addition to this, the history of the operating platform (be that a wind turbine, aircraft or train) should be recorded to determine the exact effects the failure has on the overall system.

This list is non-exhaustive, but it does help recognise that the NFF phenomenon creates time consuming problems and costly bottlenecks within the maintenance program that must be controlled by sound decision making. From a management point-of-view, three critical NFF related questions arise:

- What is the business impact of the NFF failure (e.g. on system availability)?
- Should NFF reports be investigated straight away (e.g. if it does not breach any contract agreements)?
- Should NFF event investigations be avoided in the future (e.g. NFF events potentially generate business for the system provider)?

So even though quick and accurate identification of the source of the problem might be critical (for recovery and lower costs) for the operator, its business implications will be different for the OEMs and equipment suppliers. Therefore, there seems to be mutual benefits of solving such issues, and there is encouragement to share information in between operators, OEMs and suppliers. However, organisational devotion to NFF investigations is critical (Khan, 2015). To obtain full involvement, there is a need for champions who can make sound judgements and recognise the impact of their decisions. It has been noted that for corrective maintenance approximately 75.5% of NFF costs affect the customer, 14.7% affect the supplier chain whereas 9.8% is taken by OEMs – who also worry about their customer satisfaction and brand image being damaged (Erkoyuncu et al, 2016). This is the most important asset for premium service providers.

During the course of numerous discussions with maintenance personnel, and outcomes from 3 NFF symposiums 2012-15[3], it was revealed that the OEM is reluctant to be held accountable for the mismanagement of NFF issues. However, there seems to be a strong theme to manage the product knowledge, especially regarding integration of system equipment. Modern troubleshooting requires intensive knowledge for investigations; however the current infrastructure to support knowledge management and organisational policies appear ineffective (as the tasks are becoming more demanding). In the midst of the problem are the maintenance managers who will manage their resources according to the company ethos. Therefore accountability becomes an indispensable part in any fundamental solutions for controlling NFF.

3. Critique on literature

In the organizational context, it is important to analyse the various facets of a system function and in what way its elements work together to reveal how NFF manifests itself during maintenance activities. For example, at the top-most level, a legislative body would force the law and requirements that will determine the local activities for inspection and repair, which personnel will have to follow. At this point, organizations are responsible for the quality control[4] and quality assurance[5] of the maintenance system and any troubleshooting process. Failure to carry out these two activities can cause maintenance errors and inefficiencies – resulting in financial issues.

Typically, an organisation's maintenance plan would typically support actions at three levels:

[3] For a list of outcomes from the NFF Symposium, see Khan (2015)
[4] Carrying out inspections and auditing actions from regulatory bodies, e.g. the Civil Aviation Authority
[5] The function includes checking engineering change orders, auditing and investigating maintenance activities and components for errors, and examining records.

1. Strategic level: Priorities and critical targets are established in accordance with business goals. The strategic level is represented by senior management.
2. Tactical level: Resource requirements to achieve the maintenance plan are determined which include requirements, planning and scheduling. The tactical level is represented by mid-level management.
3. Operational level**:** Maintenance tasks performed in the scheduled time. The operational level is represented by the maintenance staff.

Generally, the staff at the operational level, which encompasses the 'work on the ground', have a good understanding of the NFF phenomena; testing and repair work takes place here and the operational level personnel are the ones who will identify a NFF. This is due to the nature of the problem as it appears primarily during system operation and hence the on-field personnel are the first ones to experience its consequences. It is at this stage that NFF has the potential to economically affect the system operation due to incorrect fault diagnoses, wastage of resources and unproductive time utilization that adds to maintenance costs, downtime and unavailability of the system. It can further damage the reputation and relationships within the supply chain, which is where the tactical level will get involved as they experience the shortage of spares, and the time their maintainers spend looking for faults that cannot being isolated. Due to time pressures, the tactical level will need to make decisions as to whether to allow their staff to keep searching for the symptom-to-cause relationship of the reported fault in order to remove the NFF label; alternatively they must accept the NFF and send the equipment back through the certification loop, or order further investigations by sending the equipment to a deeper level of maintenance. At the strategic level, NFF events do not inflict an immediate financial impact, due to a lack of benchmarks, and hence they struggle to understand the long term consequences that NFF events inflict on engineering practices. However, decisions made at the organisation's strategic level directly influence the tactical and operational performances. It is suggested therefore that if the cost of NFF at the strategic level were clear, it would enable NFF resolution to become an integrated part of the continuous improvement strategy of the organisation. This has been the subject of many discussions, and helps clarifies why the NFF phenomenon has not been able to attract much attention for resolution, despite being a known issue for many decades (Khan, 2015).

Roberts et al (1994) have argued that there are three characteristics that influences decision making within organisations; these include high accountability, low familiarity (or routine with the situation) and high political stake. Contrary to this, Hart et al. (1993) established that high time pressure was a key characteristic for situations where the decisions making process takes place at the bottom of the management hierarchy. The propositions by Roberts et al. (1994) and Hart et al. (1993) are related to how key decisions actually move in industrial organisations under operational pressure – it is a notable gap in current NFF knowledge regarding characteristics that limit its decision making process. Making use of an NFF policy can help bridge this gap and regulate the problem.

So what influences individuals when making decisions related to NFF events and what should its policy entail? Let's explore this question in the context of accountability, the culture of the organisation; the experience of individuals in making NFF related decisions, the operational environment and pressure:

1. Accountability: According to Roberts et al. (1994), high accountability leads to people making more accurate decisions, whereas on the other hand according to the second proposition "intense accountability leads to feelings of high responsibility which are relieved by ranching[6] decisions up in the organization". This implies that perceived high accountability is a characteristic that enhances the decision making upwards within the management hierarchy of an organisation. Therefore, NFF investigations should not just be a peripheral activity rather it must be reflected within its senior management in order to establish mutual perceptions with regards to the consequence of NFF on the maintenance budget. Managers participate in (or facilitate) the decision-making process for the allocation of resources, the development and implementation of strategic plans, the establishment of intervention and control strategies. Due to their role, managers implement strategies and practices that aim to improve standards and other related tasks. It should be clear by now that the influence of NFF, on maintenance plans and system availability, is far more evident to maintenance managers. This is supported by several cogent arguments which indicate the complexities within commercial contracts, organisational bureaucracies and the lack of adequate metrics for costing the impact of NFF units within the supply chain. Therefore, a policy must recognise the role of senior management as a vital function in the need to improve supporting actions and budgeting for NFF reduction.

2. The culture of the organisation: An organisation's culture evidently has similarity with human factors but tends to describe the corrective aspect rather than the individual. They have been recognised to be exceedingly bureaucratic and difficult in their response to

[6] To cause something to rise (or fall) as a step in what is perceived as an irreversible process

changes; hence not recognizing NFF as a problem (Khan et al, 2015). However, many practitioners agree that one of the most significant contributory factors of NFF events are attributed to the behaviour, skill sets and communication between an organization's technicians, engineers and management personnel.

“The problem here lies more at the human level as there are so many human failings related to the variety of ways that faults are reported, the ways maintenance manuals that are written and presented, and the ways troubleshooting tests are designed. Adding the mix of training, expertise and experience that each engineer has in troubleshooting will affect how a company approaches NFF events. However, there are often insufficient resources to repair items on time, as well as not enough information, training and tools.” (Khan, 2014a).

Reasons that are often recognized are similar to those acknowledged at the individual levels – that affect individual behaviour:

1. Lack of communication
2. Not following the correct process
3. Workforce behaviour
4. Lack of training
5. Operational pressure

3. The experience of individuals in making NFF related decisions: Troubleshooting processes are affected not only by training and tools, but are also heavily dependent upon experience. This is important as increased levels of system complexity are a major cause of NFF events and the experience of maintenance personnel is critical to provide system familiarity. When the system is complex, unless the maintainer is knowledgeable or experienced, they will simply send the whole unit for repair rather than carry out further troubleshooting to identify the component at fault. In operational conditions, there can often be a lack of expert knowledge for fault diagnosis due to their unavailability – perhaps due to different shifts, sickness, or a holiday. This. Khan et al (2014a) summarised the current challenges of on-site experience:
    1. To store this experience-based knowledge, and deliver it at the time and place that the same problem symptoms occur, so that it can be re-used to help solve the problem on the first attempt.

2. To deliver that knowledge in a form that is useful to experts and less-experienced technicians alike.
3. To share this knowledge so that everyone benefits from the experience of others.
4. To integrate the knowledge access with the existing troubleshooting tools so that it becomes part of the usual troubleshooting workflow.

4. Operational environment: Environment interactions can be broad based in the context of:
   1. Physical environment – includes the physical environment as the workplace, such as the maintenance hangar or workshop
   2. Working conditions – includes working patterns, management structures, training and company organizational structure.

   Environment related implications, cannot be ignored as they potentially have the most significant impact on the behavior of maintenance staff and influence their ability to undertake effective fault diagnosis. Aviation maintenance is generally undertaken in a fast-moving environment where engineers are regularly challenged by time pressures, limited supervision and difficult working conditions, which can result in human error. Lack of time and associated pressure is a major issue within aviation maintenance due to the penalties such as financial and reputational, if the aircraft is not available for its role of carrying fare-paying passengers, which is the primary source of income for operators.

5. Decisions about NFF events can be influenced by time pressure and high uncertainty. Kruke and Olsen (2012) noted that the more complex a problem, the higher in the organisational hierarchy decisions tends to be made about them. However, the fact is that to solve and make decisions about a problem, it is essential to understand it – this is why many engineers agree that their management hierarchy does not recognize the gravity of the NFF phenomena, as no metrics exist which can estimate and present its impact to them.

4 Research Methodology

This study, on the NFF decision making process, has actively been involved with maintenance engineers from defence and civil aviation backgrounds.

Figure 2 illustrates the adopted research methodology. A key component within the research was the application of a robust data collection phase that can effectively capture data from the targeted maintenance chain. The authors of this paper have placed emphasis primarily on gathering information from maintenance engineers and related managers; but other personnel in technical support services were also included. The scope of participants involved covers a wide range of systems, i.e. legacy/modern platforms, young/experienced maintainers and operators/ supplier/OEM. This is an important factor as several personnel adopt different practices on systems depending on their systems, experiences and business requirements. The choice of the research approach is also supported by Maylor & Blackmon (2005) who advocate that investigating case studies are a useful way to study a phenomenon and its constituents in a real life setting.

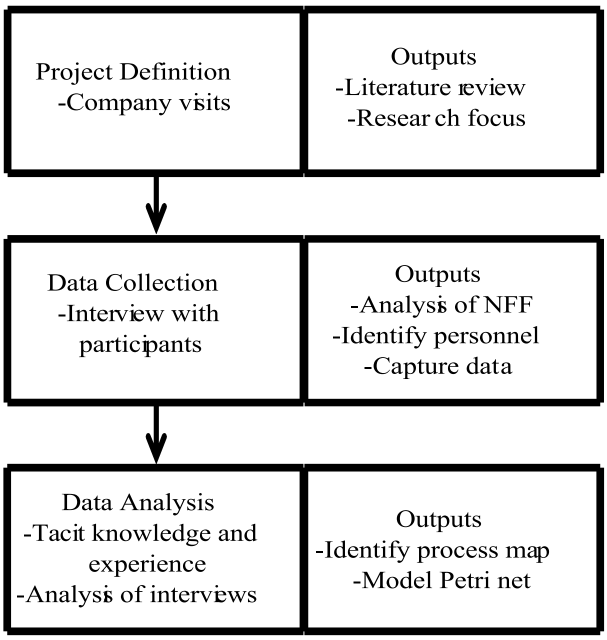

Figure 2: Adopted research methodology

Before continuing any further, the authors would like to outline the assumptions associated with the research:

- The research work is carried out by competent personnel
- All participating maintenance personnel provided their understandings based on their individual experiences and were not influenced by any pressure
- All participants are familiar with the NFF phenomenon and the challenges it presents

Also, there were a number of research limitations that were also identified:

- Variation in NFF terminology

- Limited access to sensitive industry NFF data and statistics
- A reluctance in organisations to provide realistic responses to questions
- A time limit on the academic literature review was placed from 1990–present
- A large response from a particular organisation may skew overall results

Interviews: After an introduction to the aims and objectives of the interviews, the participants were advised to generously discuss their experiences while focusing on events related to NFF risk management and decision making. The shortest interview was about 40 minutes and the longest lasted at 2 hours. In total, around 6 hours were spent during the interview discussions. Also, interviews were recorded with the agreement with the participants and where appropriate, non-disclosure agreements were signed with their organisations. The organisation type of the participants consisted of 1 operator, 2 OEMs and 2 suppliers. Table 1 presents an overview of the participants represented as in the following roles or functions:

Table 1. List of participants

	Job title	**Years of experience**
Participant 1	Reliability engineer	12
Participant 2	Airworthiness manager	8
Participant 3	Reliability manager	8
Participant 4	Technical director	18
Participant 5	Service management	14

Data collection: As groundwork for the interviews a brief checklist was developed within areas that were highlighted during the state of the art (Khan et al 2014a, Khan et al 2014b), and hence would be relevant in giving insights on how decision making moves within the organisation. The questions were prepared based on the process proposed by Roberts et al. (1994). From the literature review, it was evident that the major causes for this problem not only include technical or design errors but human factors like organisational, procedural and behavioural aspects as well. Hence, apart from the questions related to the case study and fault diagnostic process, general questions related to NFF phenomena were also addressed during the interview in order to get the participants' perspective with regard to the human factors issue.

In order to map the decision making process a questionnaire template was developed to capture the details of different diagnostic stages, as covered in Table 2. These included queries surrounding the fault reporting, detection and data recording processes.

Table 2 lists some of the basic questions used during one-to-one interviews.

Data collection	Questions utilised to investigate the problem
Management process	Does your organisation have a policy on NFF? if yes, how do you implement it? Do you recognise NFF as a major problem? How do you benchmark NFF costs and resources? Do you have dedicated NFF managers? What are the barriers to NFF issues that stop you from investigating them? In your opinion, what enhances the NFF decision making process? Can you please give an example (from your experience) about your management's attitude towards NFF events?
Case study information	Can you provide a brief description of the system/service your organisation delivers? Do you use any system modelling techniques? What are the major NFF susceptible components used in the system? Can you provide technical diagram, drawings, pictures?
Reported fault	What was the reported NFF fault's consequence? How often it has been reported/ occurrence rate? Who reports the fault? How are these reports escalated? What were the fault indicators? Has the process changed over time?
Fault reporting process	Who are the actors involved in the reporting process? What are the actions taken; how was the reporting done? What is your experience with the process? What were the testing procedures?
Fault detection process	Who are the actors involved? What are the actions taken by each actor? What is the experience of each actor?

	At which level, or who concluded the event as an NFF? What were the actions taken to identify the root cause?
Data recording process	Do you record maintenance data? Do you have any specific data recording method? Do you share this data with others? Do you make use of maintenance data history for problem diagnostics Is it used for training purposes of new engineers and technicians

Based on the authors' own experiences in a project environment, factors concerning political sensitivity and career concerns where accounted for by speculating the direct economic impact of decisions and whether if their consequences on customer perception. Other sensitive areas in this context were to speculate about how internal departmental interactions and relations between maintenance personnel influence the decision making processes. It is expected that maintenance personnel will endeavour to push away the NFF decision making process in cases where they experience high accountability. Based on this, questions were formed around the situation and problem escalations instead. Another area that was explored was if the decision making process was influenced by ad hoc procedures, e.g. influences from steering groups, cross industry knowledge, informal communication, etc.

5 Decision making in a value led organisation

High competition and under time pressure: The participants were asked a series of questions to ascertain the business and time pressures they were under in their regular job. In a civil aviation environment, operators are under tremendous pressure to get the grounded aircraft back in air to generate revenue. Therefore availability of the system is paramount to the business – perhaps more than quality of service. Regardless of how contracts are agreed, investigating NFF issues results in wasted efforts, delays and affects reputation.

It is revealed that the decision making during this phase is usually managed on the tactical level (or higher). There is no transfer of decision downwards on the organisational hierarchy at this stage. Participants 4 and 5 both admit that the decision making is driven and focused by considerations of the competitive situation at hand, as well as the strategic importance. Participant 5 explained that a key driver behind decisions is that the organization is cautious about customer satisfaction and hence will focus on addressing NFF reports. Customers are becoming more assertive about the cost and resolution of these problems: *"they replace an LRU*[7] *and observe that the fault goes away, but the maintenance organization cannot find the fault and has to (directly or indirectly) charge the customer for it. If this is the case, then, there is no problem, and we are advised to bury our heads in the sand and concentrate on the business coming in and not what we are losing…"*

Bureaucracy increases the friction between the two sides. These views are of course subjective, but it is necessary to acknowledge the fact that at some organizational level an event had occurred, and some decision was taken that has resulted with an NFF decision during maintenance. On reflection of their situation, participant 4 emphasized the fierce competition amongst suppliers – where the operator (or service provider) has existing equipment from various other OEM's, claimed that unless the NFF events are resolve effectively, they would stop doing business with the supplier in the future.

Both participants 4 and 5 acknowledge how high stake decisions are made (both in pure and direct monetary terms). Due to business demands and the strategic importance of getting the contract, NFF related decisions making keeps moving to the strategic level. According to them, this is a good sign as their organisations have initiated measures for managing the NFF decision making process by:

- Adopting the ARINC 672[8]
- Investing in training

Key stakeholder criticism: Even though NFF is not explicitly recognised within their contracts, the maintenance managers make a conscious effort to keep key stakeholders informed about the rogue units on a regular basis to avoid any criticism. According to participant 4, this initiative started as bi-weekly bulletins to foster knowledge sharing and to open up a communications channel between their organisation and its customers. The technical director further explained that the purpose was

[7] A Line replaceable Unit (LRU) is a modular component that is designed to be replaced quickly at an operating location. It is usually a sealed unit, used to improve maintenance operations, because they can be stocked and replaced quickly from on-site inventory, restoring the system to service, while the failed LRU is undergoing maintenance. Because they are modular, they also reduce system costs and increase quality, by centralizing development across different system platforms.

[8] The ARINC 672 is a set of NFF guidelines that were introduced a generic procedure that can help understand the fundamental principles, relationships, mechanisms and interactions connected to NFF failure situations. It provides criterions for decision taking regarding root causes, and describes the importance of taking maintenance actions at an early stage of the component repair cycle. It further highlights the necessary means of reducing costs by avoiding unwanted removing units from the aircraft (Khan et al, 2014a).

to share information in order to secure that all key stakeholders were acting based on the same information.

Furthermore, the ambition to keep a wide forum of stakeholders informed also indicates a means to avoid self-reproach in case situations should affect later – by being able to argue that many people were aware of what was going on and could have taken action. On the contrary, by stating that: “we are a good organisation to work with...”, it is all about saving the situation. When reflecting over reproach on an organisational level, the director indicated that avoidance of reproach actually is a driving force behind the information sharing as it was based on personal experience of the situation and not in the organisational culture.

Lack of alternatives: When asked about such situations where critical decisions had to be made (with limited alternatives), the participants emphasized that after evaluating the possibilities, they are limited to the written procedures set out in the service manuals. In these situations, operators are usually advised to return questionable units back to the OEM for further testing.

A challenging part in aerospace maintenance can be attributed to its equipment design. With a drive towards a more electric aircraft, there is a drive towards more functional integration of built in tests. Unfortunately, much of the technical skills required to manage these systems can be limited in isolating all faults – at least to a level where only the offending equipment requires removal. In such situations, there are no alternatives as the management applications that cope with fault investigations are limited and do not provide the required visibility.

The participants voiced this concern and expressed their need for the additional fault detection alternatives within their standard testing, including for intermittent faults, transient faults and false alarms. However, there was no universal agreement on how the capability should be classified and processed, or even the level of granularity that must be included.

Deliberate oversight: When asked to elaborate why maintenance teams do not formally escalate an increase in NFF situations to their strategic level, participants 1 and 4 gave a picture of a situation that was severely influenced by organisational and personnel issues. Both participants emphasized that their teams endeavoured to manage the situation at their operational level; and in cooperation with customer as far as possible. However, at times some personnel become defensive in these situations and do not accept responsibility. It was further emphasized that the consequences of technical flaws can accumulate by a mix of problems with:

- Personal relations within the team

- Lack of overall system knowledge, or inexperience
- Insufficient personal competence together with low motivation

When there are no alternative options but to return the unit (there are no obvious technical deficiencies that showed in the unit acceptance test), the operational level made their decisions without escalation (or even informing higher management about it). Similarly, in light of the technical, organisational and personnel related issues, maintenance personnel maintained the decision making within their teams. The situation is made worse when there is not enough time to verify and validate even a small fraction of a system faults during formal testing: “An aircraft may have a fault universe of 12,000 faults… but the budget, schedule and other practical test considerations may whittle that number down to 200 highly-probable faults being tested during developmental tests”.

Further to the abovementioned, difficulties in getting attention from the strategic level also constrained the issue of decision making. Participant 3 expressed the difficulties faced with organising urgent meetings: "I tried to call for a meeting on our rogue units. First we talk internally, and then I called for meetings, but management could not join. They had other priorities. However, sometimes these issues cannot wait a week or 10 days. They needed to take place the day after or so". Participant 1 summarises his experiences with NFF events, concluding that the “our steering group is not particularly supportive as they cannot visually see the impact of the problem. We have no cost metrics, so unless there is someone who has experienced NFF in the steering group, nothing changes”. It was also mentioned that the rule of thumb introduced in the organisation is to discard a unit if it has been tagged as “NFF” three times during service – as an attempt to control rogue units in their inventory.

Participant 5 raised an opinion that a year old request for additional training support with NFF components did not materialise (at least at the time of the interview), and elaborated on the topic saying that “I believe I'm right in what I'm saying; as we see a rise in the number of such problems… no one was interested in addressing the root. OEMs make a profit from their additional testing therefore there is no incentive to solve the problem. Sometimes we just shout ‘solve the problem’ or ‘this is unacceptable’. This is why we need more training so that we can deal with them ourselves; as much as we can…. there is no help to be expected, except for the help we can give ourselves”.

5.1 Critique on NFF decision making

The literature and interviews indicate a general organisational outlook on NFF decision making as shown in Table 3:

Table 3. Organisational levels and drivers for NFF

Organisational level	**Drivers**
Strategic	Accountability High degree of uniqueness High political stake
Tactical Operational	Operational pressures Delegation of decisions

Although organisations promote and encourage delegation of decision making and support, they expect rigid structures and procedures for decision making to be implemented. It was also noted that these structures and procedures are not fully utilised, i.e. there is a considerable difference between what is expected and how it is actually done.

Moreover, the company values and culture provide a general policy with guidelines for risk, issue- and non-conformity management in commercial projects, as well as for managing customer claims and warranty issues – all decisions with a financial impact are required to follow the general authorisation routine. In these authorisation routines, specific monetary limits are set for the undersigning at different organisational levels. The picture that emerges here is that the decision making is being controlled, subject to rigid structures and seems to transfer important decisions towards the top level management.

When reflecting back on one example of NFF escalation, participant 1 describes a situation in which they did not demonstrate or utilise the existing structures for issue management: "I had escalated, e.g. in emails to Mr X and Mr Y ... but since uncomfortable decisions had to be taken… or uncomfortable calls to be made, I didn't hear back for months... I should have acted in another way and instead called for a meeting, with protocol. Now the only thing that exists is an email as evidence. I only spoke with someone and went back believing that something should happen. Then a few months later the issue came up in another forum, with another customer."

This lesson learnt is important for managers – it is necessary to be formal and evidence efforts. Furthermore, participant 1 reflecting over these matters stated: “In the beginning, most decisions are taken by the project requirements. Then, as operational pressures kick in, decisions escalate to some kind of steering group level. If nothing happens after that, the manager loses control totally”. According to Geraldi et al. (2010), political support and the sense of urgency are of great relevance for an organisation’s ability to manage events. This argument can be extended to NFF problems.

In the context of escalation, participants were asked to elaborate on the support they were given or expected to get from higher levels in the organisation; a mixed picture emerged. At one end, the organisational culture and ethos is generally perceived and described as supporting and safe for the individual, exemplified by one participant stating that “We are a very pleasant organisation to work for… no negative spiral. Instead it’s all about saving the situation and then move on. That is very positive”. However, when reflecting over and elaborating on the same topic, specifically for NFF related issues, the feedback was more critical with statements such as that “the steering group was not particularly supportive” or even as one participant described: "A highly personal reflection, but when talking about NFF costs and how to manage these, my feeling is that the function of the steering group is more like a mirror which you put up and if you shout into it you will only see yourself. To escalate and say that we have a training problem or budgeting problem … I feel that it would not help. Instead it would only have come back to us to go and solve the issue...”. The struggle for attention, support and low sense of urgency were also pointed out by participant 3 who struggled with arranging a meeting on rogue units.
These interviews evidence that due to the lack of political support and low sense of urgency, there seems to be a lack of trust to get constructive support to manage or resolve issues. This was one of the major factors that constrained NFF related decisions within the organisation. Kruke & Olsen (2012) advocate that collective understanding of an organisation’s strategies and routines imply that decision making could be transferred according to the need of the situation. From an NFF point of view, there are no obvious indications on instances where this type of understanding has succeeded. What this study does confirm is that accountability is an important characteristic. However, the perceptions of individuals involved in the situation (who subject to high accountability) play an important role. Table 4 summarises the NFF decision making drivers.

Table 4. NFF decision making drivers

What enhances NFF decision making?	**What limits NFF decision making?**

• Having alternatives • Key stakeholder involvement • Promoting group value instead of individual efforts • Strategic level policy • Informal networks • Adequate training • Organisation ethos	• High political stake (varying business interests) • Non-routine situations (inexperience) • Business pressures • Lack of management attention • Resource limitations • Lack of training • Organisation ethos

It should be clear that an organisation's culture will heavily influence all identified drivers. Many engineers (including the participants) have expressed that with complexity and high functionality come benefits but also frustration when things do not work the way they are expected to. Training (or at least clear guidance) is thus often more a necessity than a 'nice to have' option. The younger generation of engineers seems reluctant to read a manual, whereas the older generations struggle to find the manual on-line. Overall this analysis illustrates that NFF events are not just technical issues but strong cultural and experience related influences. Aspects of human behavioural understanding are therefore required to control NFF events. Therefore, the most prominent driver for enhancing/constraining the NFF decision making process is training.

5.2 Management of "decisions"

The management of NFF events can be viewed as stable cognitive processes and variations in action patterns; such as maintaining ongoing focus on reported fault, simplified diagnostic process, current organisational culture and expert knowledge (Pickthall, 2014). An effective way to control its effects will be through the use of policies. Such an approach can help in achieving objectives and can indicate a course of actions to cope with situations when they take place. However, organisations seldom define NFF related policies, and hence they rarely exist in any written form. Recently, Khan et al (2015) worked towards establishing policy requirements related to NFF events, that can help strategic level management recognise the interrelationships that exist between the various functions (or departments) of the organisation. The aim is to promote an industry-wide understanding of the principal causes that result in the NFF phenomena:

- The scope and limits of NFF events: For an organisation, this will determine what is within its terms of reference (jurisdiction) for NFF investigation, and what should be excluded. This is not an argument against including (or excluding) particular NFF events, but stress that such a decision should be on the basis of explicit directives, definitions and mutual understanding with the organisation (or sector).

- Type and level of troubleshooting expected: This refers to the amount and intensity of the troubleshooting that is expected to provide the answer if a component must be removed or not. E.g. what levels of checks are required on suspected units, how many times can a rogue unit be put back into service? As pointed out by some of the participant; their organisations have developed a rule on rogue units where they would remove a unit from service if it has been tagged as an NFF three times. Of course, such factors will rely on establishing a balance between the costs incurred and the time taken to carry out the troubleshooting process.

- Role and Responsibilities of management: Investigating NFF is not just a peripheral activity within an organisation, and this must be reflected within its senior management in order to establish mutual perceptions with regards to the consequence of NFF on an organisation. Principally, managers participate in (or facilitate) the decision-making process for the allocation of resources, the development and implementation of strategic plans, the establishment of intervention and control strategies. The interviews have evidenced that political support and a sense of urgency from senior management can help resolve issues early.

- Personnel practices: Other essential factors that need to be covered within a NFF policy include reporting and training – which was recognised as the most prominent driver for enhancing/constraining the NFF decision making process. Adequate reporting can ensure that correct and sufficient data is collected and recorded to allow maintainers at all levels in Figure 1 to have the complete fault history of a suspected component. This may include reports from manufacturers (or subcontractors) with a component on its return, detailing the original fault and any work which was carried out. Furthermore, the effectiveness of a maintenance system can only be as good as the people who control it, and therefore no effort should be spared when it comes to training.

This above list provides the building blocks for an NFF policy that can assist design, management and maintenance personnel to make sound decisions. Its implementation requires sufficient knowledge regarding the business and the ability to accommodate existing requirements within available means. Now that an NFF policy requirement has been laid down, the authors of this paper would like to classify the NFF phenomenon into five key processes – which need to be controlled. The motivation for the classification is to enables simultaneous adaptive learning and reliable performance. Weick et al (2008) have suggested that these processes can help represent theoretical developments on the root cause of events. The goal here is to adapt these processes in the NFF context and use the defined NFF management policy to regulate them.

Consider the following two categories:

1. Fault detection: this deals with the processes (i) preoccupation with failure, (ii) the reluctance to simplify and (iii) sensitivity to operations.
2. Fault isolation and recovery: this deals with processes (Iv) commitment to resilience and (v) deference to expertise.

Although straight forward, for NFF investigations there might be a challenge to control these processes into practice (e.g. they warrant paying attention to failures that cannot be verified rather than successful troubleshooting and encourages getting better at being reactive instead of proactive plans). Some authors have even argued against the processes of anticipation, where "the warning signs are only obvious in retrospect and that it is often not possible to discern their significance beforehand" (Hopkins, 2007). The processes of anticipation have also been criticised from the standpoint that picking up the almost infinite number of weak signals existing in the organisational environment is far beyond the human, technological and organisational capability in most organisations. However, the authors of this paper advocate that regulated anticipation, from the standpoint that organisations that have less than their fair share of NFF problems, may be better in appreciating the significance of such events. The following discusses details of the control process:

<u>Anticipation:</u>

i. Preoccupation with failure: Preoccupation with failure is the first process of anticipation and at the heart of this process lays efforts into detecting small emerging failures. These might hold evidence about other failures elsewhere in the system, as well as identifying and specifying significant mistakes that must be avoided. Organisational success contributes to narrowing perceptions, changing attitudes, reinforcing one way of doing business and, more importantly, having the confidence in current practice. The fact is that success leads to complacency, which increases the likelihood of an NFF event going unnoticed for a long time – possibly resulting in a bigger financial problem.

This indicates that it is better to be preoccupied with failure reports instead of successful troubleshooting. Paying close attention to early NFF indicators, relentlessly searching for symptoms of malfunction, as well as sharing knowledge about mistakes engineers make, all are instrumental for the process of anticipation.

ii. Reluctance to simplify: The second process of anticipation is reluctance to simplify. To achieve higher system reliability, designers often appear reluctant to simplifications, as these are likely to increase eventual surprises and inconsistencies. Reluctance to simplify implies that "with more differentiation comes a richer and more varied picture of potential consequences, which in turn suggests a richer and more varied set of precautions and early warning signs" (Weick & Sutcliffe, 2007, p53).

    Minor failure reports act as warnings to larger problems. Being able to detect these weak signals of impending failures warrants attention to sufficient level of detail, including actively seeking to anticipate and isolate failures as they occur. To be able to predict, detect and isolate more, designers need to resist over simplifying processes and even take premeditated steps to consciously record event descriptions, as well as encouraging diversity in teams and negotiating different views.

iii. Sensitivity to operations: The final principle of anticipation, sensitivity to operations, is concerned with the job carried out, rather then what was supposed to be done. Weick and Sutcliffe (2007) elaborated on threats to sensitivity in operations:

    - The engineering culture where a high value is put on quantifiable, measurable and public knowledge rather than on the more experiential knowledge; which is often required for operators to fulfil the engineers' intentions. The author's stressed that neither of these forms of knowledge stands higher than the other.
    - Another threat is associated with the tendency of routine tasks to become mindless[9], where mindless in this context has the meaning of automatic. Careful execution of such tasks includes consciously adapting and reworking them to fit changed conditions and new learning.
    - The final threat, to sensitivity to operations, is the overestimation of an organisation's own soundness that happens when incorrect conclusions are drawn from symptoms about the root cause of the problem.

[9] i.e. acting or done without justification and with no concern for the consequences.

Containment:

iv. Commitment to resilience: Organisations recognize the inevitability of errors and therefore pay extra attention not only to error prevention and detection (anticipation), but also to containment. Commitment to resilience is the first process of containment. These processes are geared towards recovering from setbacks and restoring a systems ability to restore itself after unanticipated events.

v. Deference to expertise: Deference to expertise is the second process of containment. This process focuses on the ability to shift decision making to those with the highest expertise related to the situation at hand, irrespective of their status in the organisational hierarchy. Deference to expertise is made possible by under specification of structures[10]. Specification of structures was studied by Mannarelli et al (1996) who found that organisations reduced potential errors by delegating the decision making process and responsibility; structuring themselves to quickly move from completely centralized decision making and hierarchy, during periods of relative calm, into a completely decentralized and flat decision structures, during pressure situations. Furthermore, Weick (2006) emphasizes that both, decision making structures and the expertise, identified with specific people (or positions) are temporary. In fact, Weick & Sutcliffe (2007) make an important distinction between experts and expertise arguing that the latter is a collection of knowledge, experience, learning, and intuitions that is seldom embodied in a single individual. This knowledge usually stays hidden in the heads of few key engineers who have acquired through years of experience and training. The mission is to disseminate this knowledge to others (Khan et al, 2014b).

The next section makes use of the research work to map the NFF process within as a Petri net model. Such a model will be useful in visualising the areas where the NFF decision making can have the greatest impact.

6 Petri Nets

Petri Nets are an intuitive formal graphical representation used to model complex concurrent systems. Constructed as bipartite graphs they contain two classes of nodes, places and transitions, connected by directed arcs. Based upon discrete events they have been expanded to include stochastic, continuous, hybrid and high-level nets (Machado et al, 2009). They have been widely

[10] Under specification is the degree of specification in a decision making structure to which rules and procedures govern decision situations such that they become routinized. In contrasts, over specification is the degree of specification in a decision making structure that narrows the focus of attention (adding granularity).

used as a modelling language for a number of applications, for example manufacturing process design, workflow management and systems biology (Simao et al, 2005).

Figure 3 illustrates the basics of Petri nets which consists of places (shown as circles), transitions (shown as bars) and arcs, which can run from a place to transition or vice versa. A marking (shown as black dots) represent a configuration of a place, and consist of a number of tokens. The firing of a place towards a transition is dependent on the configuration of tokens present, upon doing so the tokens are consumed and output tokens are then created in the output place. More information on Petri nets can be reviewed in Cabasino (2009), Lin et al (1993) and Sampath et al (1995).

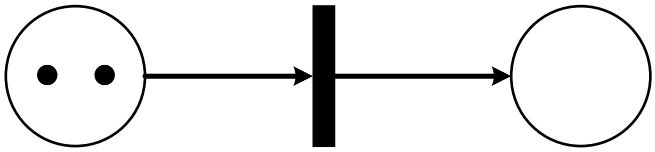

Figure 3: Petri net example

Over the years, the concept of Petri Nets has been used to study the dynamics of decision making organizations. This is carried out by using *tokens* in the places of a net and then analysing these as a result of the structure of the net and the protocols in its description (Boettcher, 1982). These models are effective in illustrating the flow of information within organizations; where the *tokens* represent information carriers that wait to be processed at *places*. These *places* are conditions which must be met before the information held in them can be processed. Consecutively, *transitions* are events that process and transform this information. This transformation could include analysis, synthesis, transfer from one point to another, or computation (Reisig, 2012).

Levis (1984) described how to express decision making organizations by a mathematical framework. This work is based on the assumption that within these organizations there are a group of decision makers who execute clear tasks; each one limited by his bounded logic[11]. When carrying out a task, the decision makers may be faced with several options – these can be represented as different algorithms to process information, decision aids, training, etc. The approach used to select from these options can have varying effects on the performance of the organization, therefore, the fundamental constituent for defining an organization is to model the interacting decision.

[11] These limits are on the amount of information that a human can understand and process.

6.1 Modelling NFF decision making

The authors explore how the NFF decision making process can be captured using the concept of Petri nets. Consider Figures 4-6 that consists of three decision making entities. The variables used in the images are listed in Table 5. In the figures, the NFF decision making process has been divided into 4 phases: problem assessment, collection and fusion, command and response selection. These phases take place within each organisation i.e. operator, OEM and supplier.

The Operator (NFF1) must make a decision if they want to spend their resources (e.g. resources, maintenance costs, etc) or not in the troubleshooting process to search for the root cause of the problem. This indicates the initial dilemma when there is an "arising" – this has been denoted by the transition/switch TSL. Depending on how the contracts have been setup, the operator also has the option to either send the suspected unit back to their system providers (e.g. the OEM, integrators – NFF2) or discard it.

Discarding a unit can be expensive and hence is not the preferable choice. If the unit is not sent back, the operator will use their own experience and troubleshooting strategies to investigate the problem and make a decision. If unit is sent back to the system provider, they need to make sure they also send over extra situational information – such as the environmental conditions, basic tests carried out, etc.

When the NFF2 (Figure 5) receives the unit, they need to make the decision to either:

1. Do extra tests to find the problem
2. Return the unit back to the operator if they cannot find anything wrong with the unit
3. Send the unit to the supplier for further tests
4. Discard the current unit and send the operator a new one

The first two options are standard practices. The latter two options are expensive solutions to problem – which carries no guarantee that it will address the root cause of the NFF arising at the operator[12].

[12] It could be that there is no technical problem with the suspected unit, and the NFF event is related to a human factors problem at the operator's end.

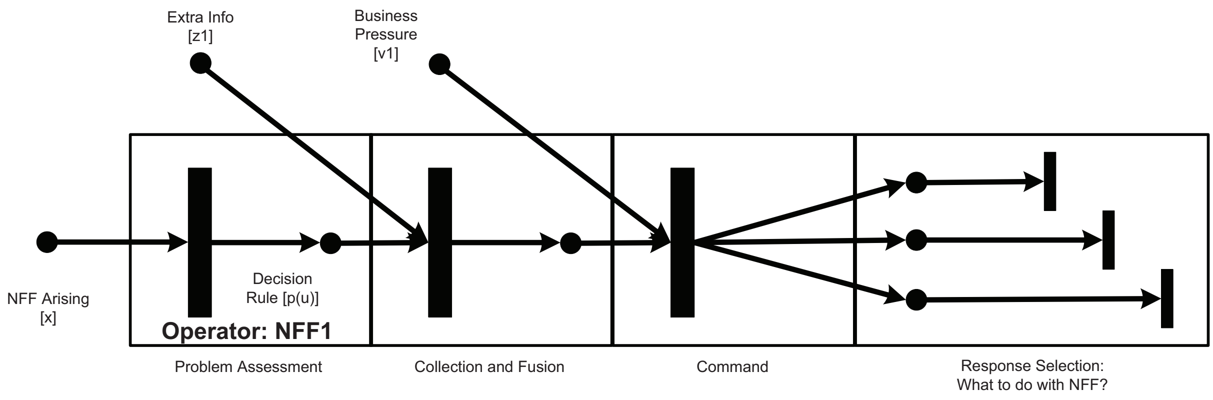

Figure 4: The NFF process map at the operator

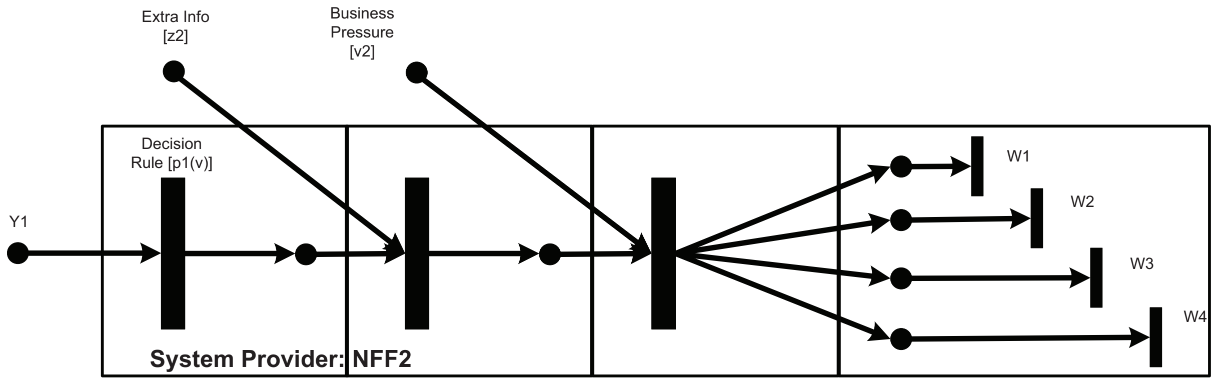

Figure 5: The NFF process map at the system provider

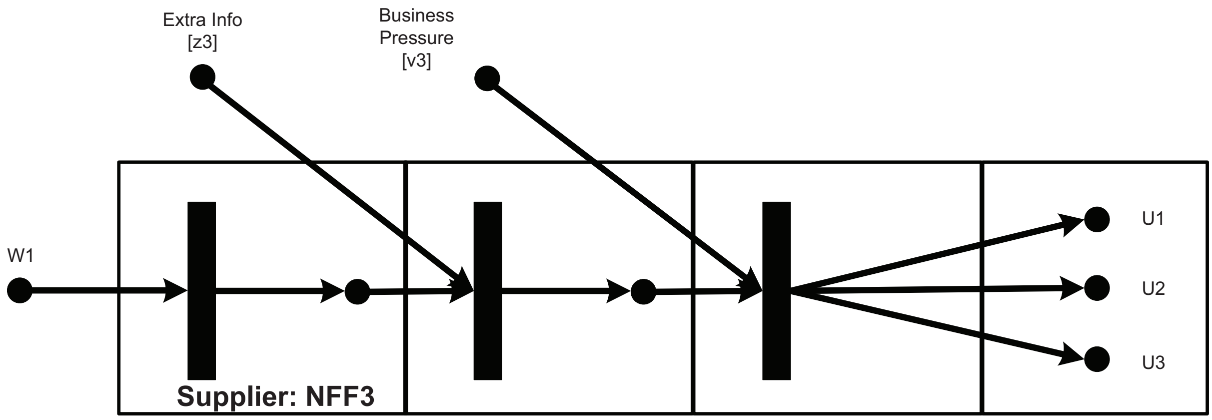

Figure 6: The NFF process map at the supplier

Table 5: List of variables and their definitions

Variables	Definition
z	is an assessment of the situation that we have an NFF component
P(u)	is the number of diagnostics you run to clear the problem
z1	Operating environmental information
z2	Simulative environmental information
z3	Unit environmental information

z'	revised assessment
v1,v2,v3	management and business pressure
Y1	send unit to system provider
Y2	do not send unit, solve problem yourself
Y3	do nothing/ignore
W1	Send unit to supplier
W2	Send unit back to operator
W3	Do extra tests on unit
W4	discard unit and send new one to operator
U1	send unit back to system provider
U2	Do extra tests
U3	discard unit and send new one to system provider

Depending on the organisation's reputation and how their business relations are with each other, it is likely that the choices might be evident to some members of the organisation. However, there is still a high degree of ambiguity surrounding the phenomenon.

Note: The further up you go with NFF1, NFF2… NFFx, the more difficult is becomes to relate the symptom to the root cause. This is will also incur greater costs. This is not only due to the business interests of each organisation, but also the lack of information surrounding the problem context – unless these organisations have some communication channels open.

6.2 Discussion

The case studies showed how firms manage integrated NFF related information flow around and how this can play an important role in their accountability for industrial maintenance delivery. This accountability concerns the ability to promptly take actions without reducing the quality of decisions. The ability in supply chains is impacted by partnership uncertainty which is due to partner involvement, relationships and behaviour. Partnering impacts on industrial maintenance targets when the services are delivered as part of networks and the sharing of information is central to long term thinking inside networks. Within major firms that provide aerospace services, the potential for partnership uncertainty is confronted primarily through an emphasis on congruity for technology platform supported by industrial maintenance and on strategizing service phase duologues between customers and partners through the use of bespoke and third party information systems.

Uncertainty associated with delivering industrial maintenance is experienced across the supply network. Uncertainty entails a difference between anticipated or predicted outcome and future actual outcome (Refsgaard et al, 2007). There are two forms of uncertainty: 1) Ambiguity: Derives from lack of information or knowledge i.e. fuzziness or ambiguity, 2) Fundamental: Unimaginable future event. Hence, uncertainty is driven by both lack of information and poor timeliness of its availability.

Within the NFF context the operator faces uncertainty in a number of areas including the problem definition process, and in defining what action needs to be taken. The problem definition is uncertain due to a lack of knowledge about the amount of effort required to realise whether NFF is experienced. In this process the number of diagnostics run will vary depending on system criticality, safety concerns and budget constraints. A major source of the uncertainty in this process is associated with the availability of reliable and comprehensive data about the operating environment. Analysing such data can offer an insight into the root causes of NFF events. The operator also faces uncertainty to choose a suitable action to resolve NFF. In this process various options are present such as sending the unit to the system provider, solving the problem yourself and doing nothing. The uncertainty of each option has cost and performance impact that needs to be measured.

In contrast to the operator the system provider faces uncertainty over the number of units that will be sent. In this instance a lack of information flow about the equipment utilisation and health will create further challenges in terms of making resources available to respond to the operator needs. In this process the degree of business pressure is also uncertain, which can also affect the resources available. Hence this may affect the duration it takes to get a unit fixed or replaced. For example, if the unit is considered to lack commercial advantages the system provider may consider terminating the provision of the unit and creating obsolescence challenges. Obsolescence refers to the unavailability of parts, or services, that were previously available (IIOM 2015). The existence of obsolescence opens up a range of options to resolve its impact on operational readiness. The options range from system redesign to emulation, reclamation and last time buy. An extreme resolution of this process would be sourcing counterfeit units from suppliers that would harm the system, whole life costs and create further safety concerns.

The supplier to the system provider also faces uncertainty in the supply network, whereby similar to the system provider the number of units to be received can be highly variable and a lack of information flow (e.g. environmental conditions) from the operator down to the supplier can create further challenges with handling NFF. Furthermore, in the process of responding to the system operator regarding the provided unit various options are present with sending the unit back to the system provider, doing extra tests and sending a new unit to the system provider. Each of these options will be influenced by business pressures and the environmental information available, which are also uncertain variables.

Overall, uncertainty of NFF is a major factor that needs to be considered when considering the life cycle of equipment. In this process, uncertainties need to be adequately considered in order to evaluate the potential impact on cost, equipment performance and safety. Furthermore, the ability to evaluate the dynamic behaviour of equipment health at the early stages of the life cycle is becoming increasingly essential due to commercial interests to evaluate provider profitability and customer affordability and supplier sustainability.

In addition to the theoretical developments, the graphical representation of the NFF process is illustrated as a conceptual model by the use of a Petri nets. This is based on the captured knowledge regarding NFF decision making in the participating organisations. It reveals the dynamic behaviour of the problem; however, its mathematical interpretation is still work under progress. Since NFF decision making is influenced by several factors, a Petri nets is a powerful tool that can help understand the complex situations that manifest NFF issues.

7 Conclusions

No Fault Found (NFF) is a major problem for organizations that rely on the functionality of assets or systems. Downtime as a result of failure or in the case of NFF uncertainty over the function of the asset is a costly problem. There are a number of drivers that impact on NFF within an organization, from the technical aspects, to the asset and human factors often in relation to maintenance procedures but also decision making plays a key role in the entire organization. Being able to quantitatively understand the effect that decision-making has on NFF within an organization could have profound impacts on reducing the costs associated with NFF.

The paper focused on the aerospace perspective of the NFF decision making process; providing in depth discussions of decision-making through interviews and questionnaires undertaken across three large organizations. This work confirms existing attitudes towards the phenomena and investigates what influences its decision making. The research shows that, contrary to loosening the organisational structure and allowing freedom in decision making (by the individuals most suitable to manage them), resolution of NFF events requires more control and escalation channels under high pressure situations. So far, there exist ad-hoc approaches that are neither documented nor shared for knowledge distribution. The interviews carried out also reveal that effective NFF management is not always carried out based on sound reasoning. Instead, it has been a result of the perceived lack of alternatives, lack of management attention and even the lack of trust in the management's ability to provide the appropriate support.

After acknowledging the industrial attitudes, the authors attempted to divide the NFF problem into five key processes that must be controlled to mitigate such issues. These processes reflect certain characteristics of NFF events: i.e. (i) investigating intermittent failures, (ii) the reluctance to simply procedures and designs; which can reduce complexities that lead to NFF events, (iii) how investigation are carried out, (iv) not adding any resilience to processes, and (v) the tendency to shift the decision making process. The motivation for this classification is to improve understanding of the root cause and context of NFF events.

Future work: Now that the authors have successfully outlined the drivers affecting the NFF decision making process and its initial model, there is a plethora of research work that can be carried out. The immediate steps are to:

- Investigate the impact of the developed NFF policies within the three participating organisations.
- Drive the mathematical formation from the Petri net model. The developed meta-models can now be work towards a unified framework to NFF issue formulation. Such a modelling approach can be used by organizations (within the whole supply chain) for operational and strategic management decision-making to investigate different scenarios and alternatives incorporating various constraints and priorities.
- Use a sensitivity analysis to identify the high impact or dominant areas for NFF decision making within the management hierarchy. A Petri Net-based approach can enable decision making with added knowledge and capability for addressing semi structured and ill-structured NFF events.
- Finally, the research aims to incorporate this knowledge in benchmarking tools to serve as key performance indicators for NFF problems.

Acknowledgements

The authors would like to express their thanks to all participants, for their time and views on NFF problems, and to Professor Rajkumar Roy for his valuable support and enthusiastic encouragement given throughout the research. Also, critical comments and constructive suggestions, from the guest editor, Professor Tetsuo Tomiyama, and the anonymous reviewers, are much appreciated.

References

(Baines et al, 2009) Baines, T. S., Lightfoot, H. W., & Kay, J. M. (2009). Servitized manufacture: Practical challenges of delivering integrated products and services. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *223*(9), 1207-1215.

(Baines et al, 2007) Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., and Wilson, H. (2007). State-of-the-art in product-service systems. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *221*(10), 1543-1552.

(Baines et al, 2009) Baines, T. S., Lightfoot, H. W., Benedettini, O., & Kay, J. M. (2009). The servitization of manufacturing: A review of literature and reflection on future challenges. *Journal of Manufacturing Technology Management*, *20*(5), 547-567.

(Barros, 1997) Barros, F. J. (1997). Modeling formalisms for dynamic structure systems. *ACM Transactions on Modeling and Computer Simulation (TOMACS)*, *7*(4), 501-515.

(Bigley and Roberts, 2001) Bigley, G. A., & Roberts, K. H. (2001). The incident command system: High-reliability organizing for complex and volatile task environments. *Academy of Management Journal*, *44*(6), 1281-1299.

(Boettcher, 1982) Boettcher, Kevin L., and Alexander H. Levis. "Modeling the interacting decisionmaker with bounded rationality." *Systems, Man and Cybernetics, IEEE Transactions on* 12.3 (1982): 334-344.

(Cabasino, 2009) Cabasino, M. P. (2009). *Diagnosis and identification of discrete event systems using Petri nets* (Doctoral dissertation, Ph. D. Thesis).

(Cabasino et al, 2008) Cabasino, M. P., Giua, A., Hadjicostis, C. N., & Seatzu, C. (2008, May). Fault model identification with Petri nets. In *Discrete Event Systems, 2008. WODES 2008. 9th International Workshop on* (pp. 455-461). IEEE.

(Erkoyuncu et al, 2016) Erkoyuncu, J. A., Khan, S., Hussain, S., & Roya, R. (2015). A framework to estimate the cost of No-Fault Found events. International Journal of Production Economics, 173, 207–222.

(Hart et al, 1993) Hart, P. T., Rosenthal, U., & Kouzmin, A. (1993). Crisis Decision Making The Centralization Thesis Revisited. *Administration & Society*, *25*(1), 12-45.

(Hopkins, 2007) Hopkins, A. (2007). The problem of defining high reliability organisations. *National Research Center for Occupational Safety and Health Regulation. January*.

(Kahne, 1983) Kahne, S. (1983). Control migration: A characteristic of C 3 systems. *IEEE Control Systems Magazine*, *3*(1), 15-19.

(Khan et al, 2015) Khan, S., Phillips, P., Hockley, C., & Jennions, I. (2015). No Fault Found: The Search for the Root Cause. Published by SAE International, ISBN: 978-0-7680-8122-0.

(Khan, 2015) Khan, S. (2015). Research study from industry-university collaboration on "No Fault Found" events. *Journal of Quality in Maintenance Engineering*, *21*(2), 186-206.

(Khan et al, 2014a) Khan, S., Phillips, P., Jennions, I., & Hockley, C. (2014). No Fault Found events in maintenance engineering Part 1: Current trends, implications and organizational practices. *Reliability Engineering & System Safety*, *123*, 183-195.

(Khan et al, 2014b) Khan, S., Phillips, P., Hockley, C., & Jennions, I. (2014). No Fault Found events in maintenance engineering Part 2: Root causes, technical developments and future research. *Reliability Engineering & System Safety*, *123*, 196-208.

(Knotts, 1999) Knotts, R. M. (1999). Civil aircraft maintenance and support Fault diagnosis from a business perspective. Journal of quality in maintenance engineering, 5(4), 335-348.

(Kruke and Olsen, 2012) Kruke, B. I., & Olsen, O. E. (2012). Knowledge creation and reliable decision-making in complex emergencies. *Disasters*, *36*(2), 212-232.

(Langley, 1999) Langley, A. (1999). Strategies for theorizing from process data. *Academy of Management review*, *24*(4), 691-710.

(Levis, 1984) A. H. Levis, Information Processing and Decision-Making Organizations: a Mathematical Description, Large Scale Systems, 7, (1984) 151-163.

(Lin et al, 1993) Lin, F., Markee, J., & Rado, B. (1993, December). Design and test of mixed signal circuits: a discrete-event approach. In *Decision and Control, 1993., Proceedings of the 32nd IEEE Conference on* (pp. 217-222). IEEE.

(Machado, 2009) Machado, D., Costa, R. S., Rocha, M., Rocha, I., Tidor, B., & Ferreira, E. C. (2009). A critical review on modelling formalisms and simulation tools in computational biosystems. In *Distributed Computing, Artificial Intelligence, Bioinformatics, Soft Computing, and Ambient Assisted Living* (pp. 1063-1070). Springer Berlin Heidelberg.

(Mannarelli et al, 1996) Mannarelli, T., Roberts, K. H., & Bea, R. G. (1996). Learning how organizations mitigate risk. *Journal of Contingencies and Crisis Management*, *4*(2), 83-92.

(Maylor and Blackmon, 2005) Maylor, H., & Blackmon, K. (2005). *Researching business and management: a roadmap for success*. Palgrave Macmillan.

(Petri, 1962) Petri, C. A. *Communication with Automata (Kommunikation mit Automaten, in German)* (Doctoral dissertation, PhD thesis, University of Bonn, 1962.(Cited on pages 17 and 92.)).

(Pickthall, 2014) Pickthall, N. (2014). The Contribution of Maintenance Human Factors to no Fault Founds on Aircraft Systems Engineering. *Procedia CIRP*, *22*, 59-64.

(Qi et al, 2008) Qi, H., Ganesan, S., & Pecht, M. (2008). No-fault-found and intermittent failures in electronic products. Microelectronics Reliability, 48(5), 663-674.

(Sampath et al, 1995) Sampath, M., Sengupta, R., Lafortune, S., Sinnamohideen, K., & Teneketzis, D. (1995). Diagnosability of discrete-event systems. *Automatic Control, IEEE Transactions on*, *40*(9), 1555-1575.

(Simao, 2005) Simao, E., Remy, E., Thieffry, D., & Chaouiya, C. (2005). Qualitative modelling of regulated metabolic pathways: application to the tryptophan biosynthesis in E. coli. *Bioinformatics*, *21*(suppl 2), ii190-ii196.

(Reisig, 2012) Reisig, W. (2012). *Petri nets: an introduction* (Vol. 4). Springer Science & Business Media.

(Roberts et al, 1994) Roberts, K. H., Stout, S. K., & Halpern, J. J. (1994). Decision dynamics in two high reliability military organizations. *Management Science*, *40*(5), 614-624.

(Roy et al, 2013) Roy, R., Shaw, A., Erkoyuncu, J. A., & Redding, L. (2013). Through-life engineering services. *Measurement and Control*, *46*(6), 172-175.

(Weick and Sutcliffe, 2011) Weick, K. E., & Sutcliffe, K. M. (2011). *Managing the unexpected: Resilient performance in an age of uncertainty* (Vol. 8). John Wiley & Sons.

(Weick et al, 2008) Weick, K. E., Sutcliffe, K. M., & Obstfeld, D. (2008). Organizing for high reliability: Processes of collective mindfulness. *Crisis management*, *3*, 81-123.

(Weick, 2006) Weick, K. E. (2006). Faith, evidence, and action: Better guesses in an unknowable world. *Organization studies*, *27*(11), 1723-1736.

(Weick and Quinn, 1999) Weick, K. E., & Quinn, R. E. (1999). Organizational change and development. *Annual review of psychology*, *50*(1), 361-386.

(Zeigler et al, 1979) Zeigler, B. P., & Oren, T. I. (1979). Theory of modelling and simulation. *IEEE Transactions on Systems, Man, and Cybernetics*, *1*(9), 69.

(Zhang and Chu, 2010) Zhang, Z., & Chu, X. (2010). A new approach for conceptual design of product and maintenance. *International Journal of Computer Integrated Manufacturing*, *23*(7), 603-618.

2016-06-20

A novel approach for No Fault Found decision-mak

Khan, Samir

Elsevier

Khan S, Farnsworth M, Erkoyuncu J, A novel approach for No Fault Found decision making, CIRP Journal of Manufacturing Science and Technology, Vol. 17, May 2017, pp. 18-31

http://dx.doi.org/10.1016/j.cirpj.2016.05.011